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NOSC TD 545

NOSC TD 545

Technical Document 545

COMPUTING PROBABILITY MASSES IN RULE-BASED SYSTEMS

R. A. Dillard

8 September 1982

Prepared for
NOSC Independent Research/Independent
Exploratory Development Program

Approved for public release; distribution unlimited

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This report summarizes work performed during fiscal year 1982 by members of the C^2 Information Processing Branch (Code 8242). The effort was supported by the NOSC Independent Research/Independent Exploratory Development program under program element 61152N.

Released by
R.C. Kolb, Head
Tactical Command and
Control Division

Under authority of
J.H. Maynard, Head
Command Control–Electronic Warfare
Systems and Technology Department

ACKNOWLEDGMENT

The author is grateful to R.J. Bechtel, Code 8242, for assisting with the computer experiments.

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER NOSC Technical Doc ment 545 (TD 545)	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) COMPUTING PROBABILITY MASSES IN RULE-BASED SYSTEMS		5. TYPE OF REPORT & PERIOD COVERED 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) R.A. Dillard		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Ocean Systems Center San Diego, CA 92152		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 61152N (via NOSC IR/IED Program)
11. CONTROLLING OFFICE NAME AND ADDRESS		12. REPORT DATE 8 September 1982 13. NUMBER OF PAGES 55
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Artificial intelligence
Rule-based system
Inference system
Confidence weighing

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report describes a method of computing confidences in rule-based inference systems by using the Dempster-Shafer theory. The theory is applicable to tactical decision problems which can be formulated in terms of sets of exhaustive and mutually exclusive propositions. Dempster's combining procedure, a generalization of Bayesian inference, can be used to combine probability mass assignments supplied by independent bodies of evidence. This report describes the use of Dempster's combining method and Shafer's representation framework

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in rule-based inference systems. It is shown that many kinds of data fusion problems can be represented in a way such that the contraints are met. Although computational problems remain to be solved, the theory should provide a versatile and consistent way of combining confidences for a large class of inferencing problems.

CONTENTS

FIGURES

1. INTRODUCTION

In most applications of inference systems, estimates are computed of the degree of truth of the conclusions reached by the system. The medical system MYCIN, for example, employs formulas based on Bayes' Theorem and fuzzy set theory to produce a measure of belief that the patient has disease i in the light of certain pieces of evidence [1]. The mineral exploration system PROSPECTOR uses a similar scheme to assign probabilities concerning the composition of an ore deposit [2]. A somewhat different approach involving the Shafer Representation [3] and Dempster's rule of combination [4] is used in some recently developed inference methods. Applications include a technique for identifying an emitter by using information from disparate sources [5] and a fault diagnosis technique for troubleshooting a spacecraft [6].

In a tactical Navy application, the inference rules typically involve the association and identification of radar, ESM (Electronic Support Measures), and sonar contacts. When the problem is to accept or reject the hypothesis that a contact is a particular type of ship, many of the methods of propagating confidences are applicable. STAMMER2, a rule-based system developed at NOSC, uses incremental deduction formulas similar to those of MYCIN to decide whether a contact is a merchant vessel, and also to conjecture about several

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[1] Shortliffe EH.
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American Elsevier, New York, 1976.

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Subjective Bayesian Methods for Rule-Based Interface Systems.
Technical Report 124, SRI, January, 1976.

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A Mathematical Theory of Evidence.
Princeton University Press, Princeton, New Jersey, 1976.

[4] Dempster AP.
Upper and Lower Probabilities Induced by a Multivalued Mapping.
Annals of Mathematical Statistics (38):325-339, 1967.

[5] Garvey TD, Lowrance JD, and Fishler MA.
An Inference Technique for Integrating Knowledge from Disparate Sources.
In Proc. IJCAI 7, Vol. 1, pages 319-325. August, 1981.

[6] Friedman L.
Extended Plausible Inference.
In Proc. IJCAI 7, Vol. 1, pages 487-495. August, 1981.

other platform types [7], [8]. Although these formulas are adequate for simple scenarios, they will not permit consistency to be maintained when deciding among more than a very few platform types. The best method of combining independent evidence in a consistent manner appears to be Dempster's approach, which is a generalization of Bayesian inference.

This report describes the Dempster and Shafer methods and outlines their application to tactical problems. It also discusses their experimental implementation in STAMMER and in ROSIE [9], a Rule-Oriented System for Implementing Expertise, developed by the Rand Corporation.

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[7] McCall DC, Morris PH, Kibler DF, and Bechtel RJ. STAMMER2: A Production System for Tactical Situation Assessment. Technical Document 298, Volumes 1 and 2, Naval Ocean Systems Center, October, 1979.

[8] Bechtel R, Morris P, and Kibler D. Incremental Deduction in a Real-Time Environment. In Proc. CSCSI-80. May, 1980.

[9] Fain J, Gorlin D, Hayes-Roth F, Rosenschein S, Sowizral H, Waterman D. The ROSIE Language Reference Manual. Report N-1647-ARPA, The Rand Corporation, Santa Monica, CA, December, 1981.

2. THE DEMPSTER-SHAFER THEORY

2.1 INTRODUCTION

A scheme for combining evidence which includes uncertainty or ignorance was devised by Dempster [4] and later formulated within a flexible representation framework by Shafer [3]. In Shafer's representation, a "frame of discernment" on a domain is a set of propositions about the exclusive and exhaustive possibilities in the domain. The evidential interval [s(Ai), p(Ai)], a subinterval of the unit interval, may be used to represent the likelihood of Ai, the ith proposition [5]. Here, s(Ai) represents the "support" for Ai and p(Ai) the "plausibility." The plausibility is the complement of the support for ~Ai and represents the degree to which one does not doubt Ai. (The symbol "~" is the Boolean NOT.) The "uncertainty" of Ai is u(Ai) = p(Ai) - s(Ai).

The representation involves the assignment by knowledge sources of "probability masses." The mass allocated by knowledge source j to Ai is denoted m_j(Ai). The evidential interval representing evidence about Ai contributed by the jth source is then [s_j(Ai), p_j(Ai)], where s_j(Ai) = m_j(Ai) and p_j(Ai) = 1 - s_j(~Ai). The probability masses contributed by various knowledge sources can be integrated by Dempster's rule to produce m(Ai), a combined probability mass of Ai.

The terminology and notation thus far introduced closely follow that of reference 5; the notation is summarized below.

<u>Notation</u>

Ai -- ith proposition

m_j(Ai) -- probability mass -- represents the portion of belief committed to Ai by the jth knowledge source

m(Ai) -- probability mass, usually a combined probability mass

[Subscript j may be used with the remaining terms, to distinguish among knowledge sources.]

s(Ai) -- support for Ai = m(Ai)

p(Ai) -- plausibility of Ai = 1 - s(~Ai)

u(Ai) -- uncertainty of Ai = p(Ai) - s(Ai)

[s(Ai), p(Ai)] -- evidential interval of Ai.

Dempster's rule of combination requires that the knowledge sources be independent. (The same physical source, however, may contribute several pieces of sufficiently independent evidence; eg, a radar can give measures of cross section, speed, and location.) The combining operation is commutative and associative. The masses contributed by the various distinct knowledge sources can be combined in any order and in any combination of pairs, triples, etc.

2.2 SPECIAL CASE

Dempster's rule is simple to implement for the special case where the various knowledge sources assign probability masses only to the propositions Ai and to uncertainty. (The more general theory deals with subsets of the set of propositions.) For only two knowledge sources, the operation is easy to visualize. Figure 2-1 shows the component masses. The mass assigned to θ represents mass assigned to uncertainty; it is assumed to be distributed in some unknown manner among the n propositions. Specifically, we define

$$\theta = A1vA2v\ldots vAn \tag{2.1}$$

where "v" is the Boolean OR. (This definition differs from the usual one in which θ is the set of propositions {A1,...,An}.) The abscissa is a unit line segment partitioned into segments whose lengths are equal to m_1(A1), m_1(A2), ..., m_1(An), and $m_1(\theta)$, respectively. Similarly, the ordinate represents the masses assigned by KS2. The crosshatched area represents mass associated with conjunctions of exclusive propositions. Formulas for combining the masses assigned by KS1 and KS2 are given below, followed by formulas for the more general case of combining evidence from m sources. Note that when the knowledge sources contribute mass only to the propositions Ai and to θ, the uncertainty of every Ai is u(Ai) = p(Ai) - s(Ai) = $m(\theta)$.

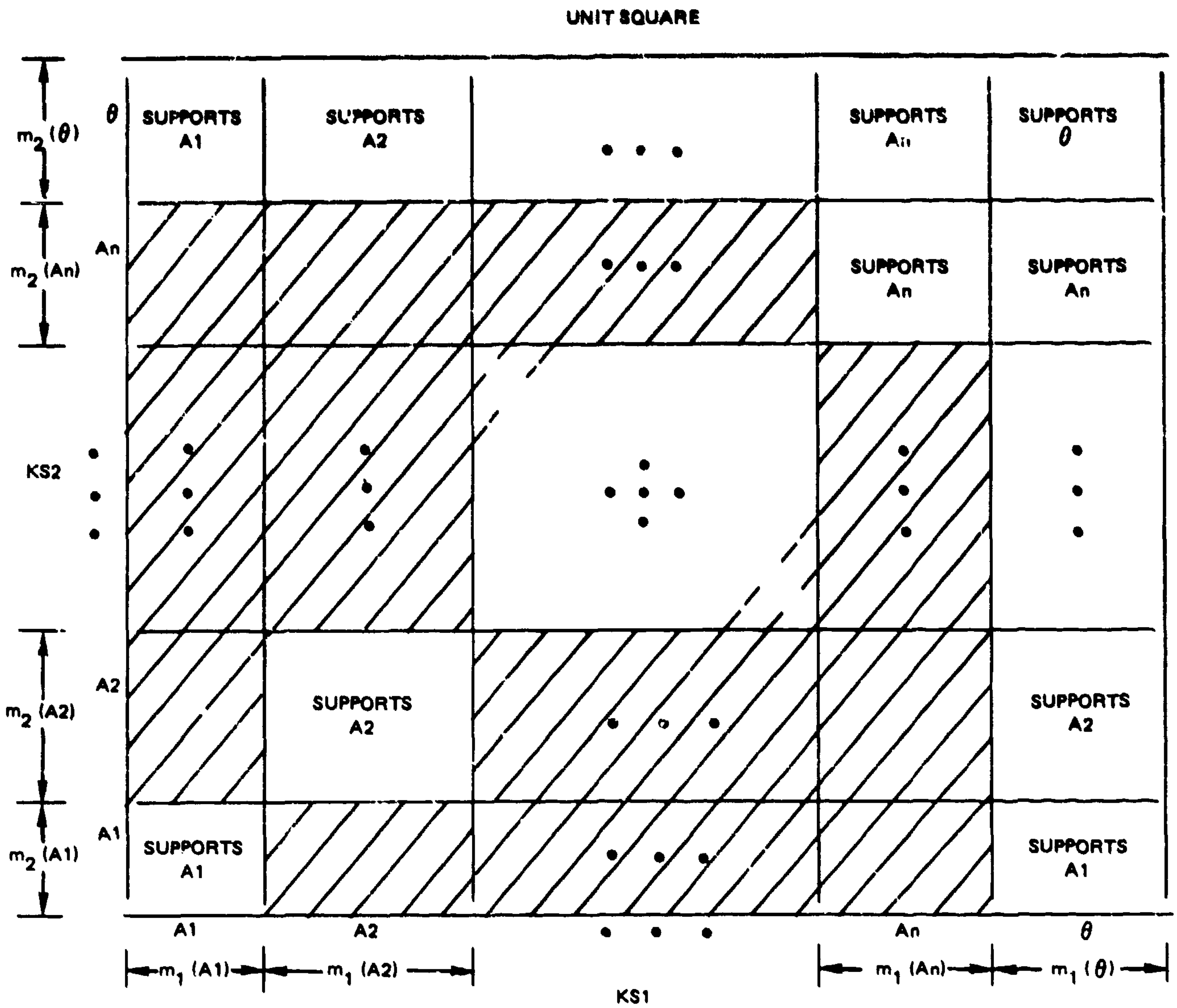

Figure 2-1. Graphical representation for two knowledge sources, KS1 and KS2, and for n exhaustive and mutually exclusive propositions.

Dempster's Rule for Two Knowledge Sources

(Special Case)

The combined probability mass for proposition Ai is

$$\begin{aligned} m(Ai) &= \{m_1(Ai) \times m_2(Ai) + m_1(Ai) \times m_2(\theta) + m_1(\theta) \times m_2(Ai)\} / C \\ &= \{[m_1(Ai) + m_1(\theta)] \times [m_2(Ai) + m_2(\theta)] - m_1(\theta) \times m_2(\theta)\} / C \\ &= F(Ai) / C \end{aligned} \tag{2.2}$$

where F(Ai) represents the expression in braces and

$$C = m_1(\theta) \times m_2(\theta) + \sum_{1 \leq i \leq n} F(Ai). \tag{2.3}$$

The normalizing factor C represents the non-crosshatched area of Figure 2-1; it restores the total probability mass to one.

The resulting uncertainty is

$$m(\theta) = m_1(\theta) \times m_2(\theta) / C = 1 - \sum_{1 \leq i \leq n} m(Ai). \tag{2.4}$$

The resulting plausibility of Ai is

$$p(Ai) = 1 - \sum_{k \neq i} m(Ak) = m(Ai) + m(\theta). \tag{2.5}$$

Note that F(Ai) can be written as a function of the component plausibilities:

$$F(Ai) = p_1(A1) \times p_2(Ai) - m_{,}(\theta) \times m_2(\theta). \tag{2.6}$$

Dempster's Rule for m Knowledge Sources (Special Case)

The combined probability mass for proposition Ai is

$$m(Ai) = \{ \prod_{1 \le j \le m} [m_j(Ai) + m_j(\theta)] - \prod_{1 \le j \le m} m_j(\theta)\} / C$$

$$= F(Ai) / C \tag{2.7}$$

where F(Ai) represents the expression in braces and

$$C = \prod_{1 \le j \le m} m_j(\theta) + \sum_{1 \le i \le n} F(Ai). \tag{2.8}$$

The resulting uncertainty is

$$m(\theta) = \prod_{1 \le j \le m} m_j(\theta) / C = 1 - \sum_{1 \le i \le n} m(Ai). \tag{2.9}$$

The resulting plausibility of Ai is

$$p(Ai) = 1 - \sum_{k \ne i} m(Ak) = m(Ai) + m(\theta). \tag{2.10}$$

Note that F(Ai) can be written

$$F(Ai) = \prod_{1 \le j \le m} p_j(Ai) - \prod_{1 \le j \le m} m_j(\theta). \tag{2.11}$$

2.3 GENERAL CASE

While an analyst frequently will be able to express his degree of belief in individual propositions, more typically he will conclude from evidence, "It's probably not a merchant" or "It's one of the ship types with a submarine-support function." The resulting mass assignments do not permit use of the special-case equations.

As an illustration of the general approach, we will use a simple example where one knowledge source contributes probability mass directly to each proposition as in the special case treated earlier and another contributes probability mass only to ~A1 and to θ. A contribution to ~A1 is treated as uncertainty mass spread in an unknown manner over A2vA3v...vAn; that is, $m_1(\tilde{}A1) = m_1(A2vA2v...vAn)$.

Using figure 2-2, we see that the probability masses for the propositions Ai are

$$m(A1) = m_1(\theta) \times m_2(A1) / C, \tag{2.12}$$

$$m(A2) = m_2(A2) / C, \tag{2.13}$$

$$\vdots$$

$$m(An) = m_2(An) / C, \tag{2.14}$$

where

$$C = 1 - m_1(\tilde{}A1) \times m_2(A1). \tag{2.15}$$

The probability mass of the uncertainty spread over all propositions is

$$m(\theta) = m_1(\theta) \times m_2(\theta) / C \tag{2.16}$$

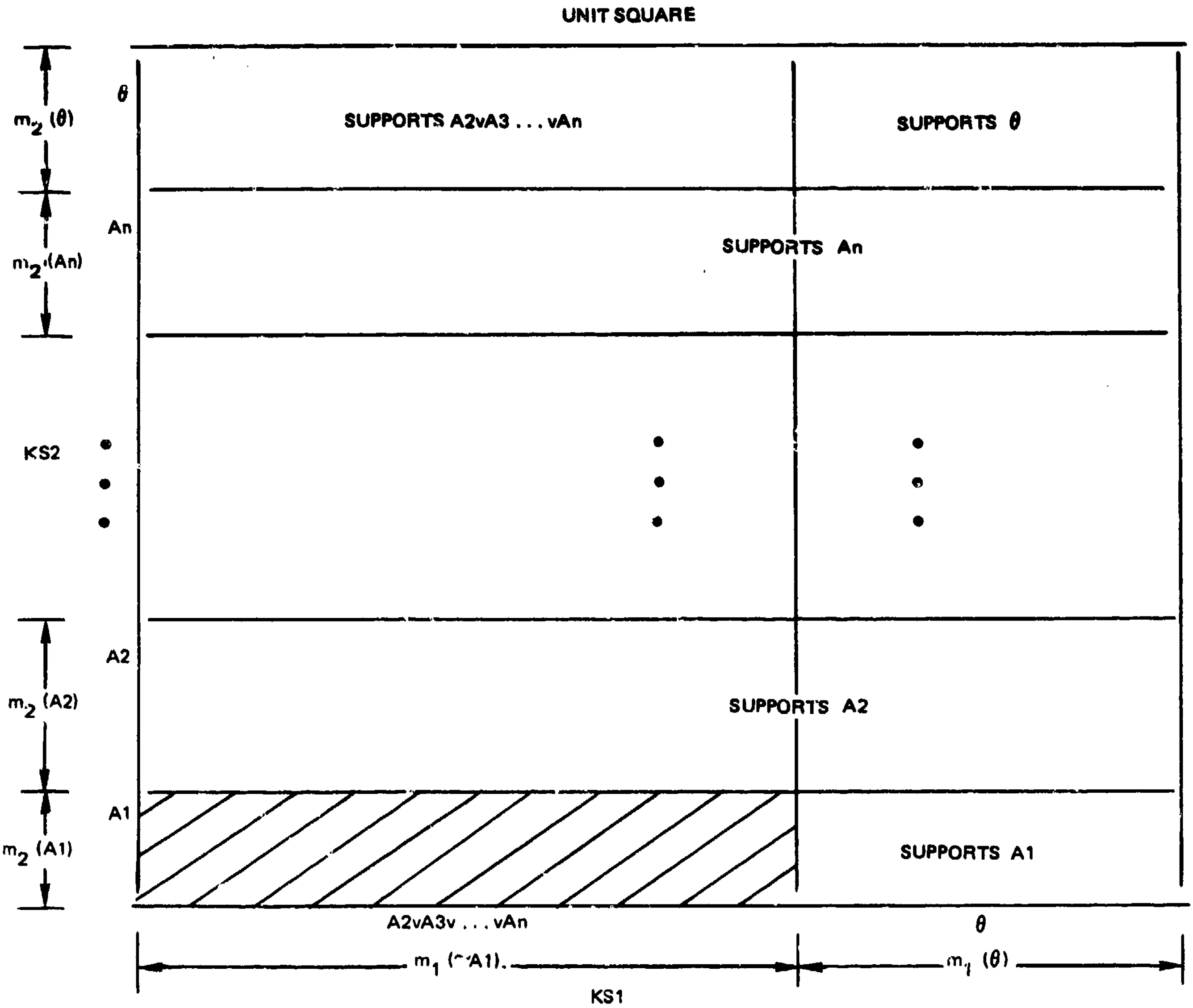

Figure 2-2. Graphical representation for two knowledge sources, KS1 and KS2, where KS1 assigns mass to ~A1 and θ.

while the mass of the uncertainty spread over A2v...vAn is

$$m(A2v...vAn) = m(\tilde{}A1) = m_1(\tilde{}A1) \times m_2(\theta) / C. \tag{2.17}$$

The plausibility of A1 is

$$p(A1) = 1 - s(\tilde{}A1) = 1 - m(A2) - \ldots - m(An) - m(\tilde{}A1)$$
$$= m(A1) + m(\theta). \tag{2.18}$$

(The formula for computing support is given shortly after this example.) The plausibility of A2 is

$$p(A2) = 1 - s(\tilde{}A2) = 1 - m(A1) - m(A3) - \ldots - m(An)$$
$$= m(A2) + m(\tilde{}A1) + m(\theta). \tag{2.19}$$

The plausibilities of the remaining Ai can be found in a similar manner. The evidential intervals of the propositions are then

A1: $[m(A1), m(A1) + m(\theta)]$,

A2: $[m(A2), m(A2) + m(\tilde{}A1) + m(\theta)]$,

.
.
.

An: $[m(An), m(An) + m(\tilde{}A1) + m(\theta)]$.

Note that the uncertainty of A1 is $u(A1) = m(\theta)$, while for $i = 2,\ldots,n$, the uncertainty is $u(Ai) = m(\tilde{}A1) + m(\theta)$.

To describe the most general case of Dempster's rule, we need to consider the set of general propositions corresponding to all possible subsets of the set {A1,A2,...,An} of exclusive and exhaustive propositions. There will be 2^n-1 such general propositions. The following example is the set of 15 general propositions for n = 4.

A1 = ~(A2vA3vA4)

A2 = ~(A1vA3vA4)

$A3 = \tilde{}(A1vA2vA4)$

$A4 = \tilde{}(A1vA2vA3)$

$A1vA2 = \tilde{}(A3vA4)$

$A1vA3 = \tilde{}(A2vA4)$

$A1vA4 = \tilde{}(A2vA3)$

$A2vA3 = \tilde{}(A1vA4)$

$A2vA4 = \tilde{}(A1vA3)$

$A3vA4 = \tilde{}(A1vA2)$

$A1vA2vA3 = \tilde{}A4$

$A1vA2vA4 = \tilde{}A3$

$A1vA3vA4 = \tilde{}A2$

$A2vA3vA4 = \tilde{}A1$

$A1vA2vA3vA4 = \theta$.

Note that the proposition $\tilde{}(A1vA2vA3vA4) = \tilde{}\theta$ is not included, since it is in conflict with the assumption that the set {A1,...,A4} is exhaustive. The impossible proposition $\tilde{}\theta$ corresponds to the null subset of {A1,...,An}.

In the representation below, the formulas for the general case involve the conjunctions of general propositions. Examples of such conjunctions, letting $i \neq j \neq k$, are

$Ai\&Ai = Ai$

$(AivAj)\&(AivAk) = Ai$

$Ai\&\theta = Ai$

$\tilde{}Ai\&Aj = Aj$

$\tilde{}Ai\&\tilde{}Aj = \tilde{}(AivAj)$

$\tilde{}Ai\&Ai=\tilde{}\theta$

$Ai\&Aj = \tilde{}\theta$

where "&" is the Boolean AND.

Formulas for combining the masses assigned by two knowledge sources KS1 and KS2 are given below, followed by the formulas for m knowledge sources. References 3 and 10 discuss the exact relationship between support functions and mass functions (in terms of "belief functions" and "basic probability assignments").

Dempster's combining operations reduce to standard Bayesian operations when $u_j(Ai) = 0$ for every proposition Ai and every knowledge source j whose evidence is combined. The advantage of Dempster's method is that ignorance and uncertainty may be consistently modeled. There is no need, for example, to arbitrarily assign initial probabilities to each proposition before evidence is gathered. When evidence is available, any uncertainty involved in the measurement or its interpretation may be adequately represented.

Dempster's Rule for Two Knowledge Sources

(General Case)

The combined probability mass of the general proposition B is

$$m(B) = \sum_{B' \& B'' = B} m_1(B') \times m_2(B'') \;/\; C \qquad (2.20)$$

where B' and B" vary over the general propositions supported by KS1 and KS2, respectively, and

$$C = \sum_{B' \& B'' \neq \sim\theta} m_1(B') \times m_2(B''). \qquad (2.21)$$

Letting F(B) denote the numerator of equation (2.20) [ie, $F(B) = C \times m(B)$], we can write

$$C = \sum F(B) \qquad (2.22)$$

where the sum is over all valid general propositions. The resulting suport for a general proposition B is

$$s(B) = \sum_{B' \& B = B'} m(B'). \qquad (2.23)$$

Equation (2.23) is needed in the calculation of the plausibility of an original proposition Ai, using $p(Ai) = 1 - s(\sim Ai)$. Note that $s(Ai) = m(Ai)$, as originally defined, and $s(\theta) = 1$. The uncertainty is $m(\theta) = m_1(\theta) \times m_2(\theta)/C$.

Dempster's Rule for m Knowledge Sources (General Case)

The combined probability mass of the general proposition B is

$$m(B) = \sum_{B_1 \& \ldots \& B_m = B} \prod_{1 \le j \le m} m_j(B_j) \,/\, C \qquad (2.24)$$

where B_j varies over the general propositions to which KS_j assigns mass and

$$C = \sum_{B_1 \& \ldots \& B_m \neq {\sim}\theta} \prod_{1 \le j \le m} m_j(B_j). \qquad (2.25)$$

Letting F(B) denote the numerator of equation (2.24) [ie, F(B) = C x m(B)], we can write

$$C = \sum F(B) \qquad (2.26)$$

where the sum is over all valid general propositions. The resulting support for a general proposition B is

$$s(B) = \sum_{B' \& B = B'} m(B'). \qquad (2.27)$$

Equation (2.27) is needed in the calculation of the plausibility of an original proposition Ai, using p(Ai) = 1 - s(~Ai). Note that s(Ai) = m(Ai), as originally defined, and s(θ) = 1.

2.4 EXCEPTIONS

When the knowledge sources are not independant, Dempster's rule does not apply. The combining rules for j dependent sources are [5]

$$s(Ai) = \underset{j}{MAX}\{s_j(Ai)\} \tag{2.28}$$

and

$$p(Ai) = \underset{j}{MIN}\{p_j(Ai)\}. \tag{2.29}$$

3. DEMPSTER'S RULE APPLIED TO PLATFORM TYPING

3.1 A FRAME OF DISCERNMENT

A "frame of discernment" was described as a set of propositions about the exclusive and exhaustive possibilities in a domain. In the application of platform identification, a "coarse" frame of discernment might be the propositions "platform x is a combatant" and "platform x is not a combatant," while the most refined frame would be the very large set of propositions of the form "platform x is <name of a specific platform>," a frame too difficult to completely formulate.

For now, we are assuming that there is one and only one platform under consideration; eg, the radar blip is not just radar noise or clutter (although sometimes we will allow it to be the return from debris) and is not the return from two platforms close together. To simplify the discussion, we will consider only surface and subsurface platforms and will disregard the possibility that a contact which appears to be a surface platform might be an aircraft. In some cases an "observed characteristic" of a platform will result from successive observations of a platform, and we will assume that the successive observations are indeed of the same platform. With these assumptions, we can let a frame of discernment be the set of exclusive and exhaustive propositions

A1: Platform x is type 1,

A2: Platform x is type 2,

.

.

.

An: Platform x is type n

where some types of lesser importance are lumped together to keep n relatively small.

To construct an example of the use of Dempster's rule, we arbitrarily specify the following types.

Ai: Type i

A1: carrier

A2: cruiser

A3: destroyer

A4: frigate

A5: amphibious

A6: submarine (surfaced or periscope/snorkel/antenna)

A7: small fighting ship (eg, corvette)

A8: fast attack/patrol craft

A9: patrol craft

A10: intelligence collector (eg, AGI)

A11: survey/research (navy operated)

A12: fleet auxiliary - medium & large

A13: fleet auxiliary - small

A14: small boats (navy and commercial)

A15: merchant

A16: fishing

A17: other commercial & private

A18: debris.

Proposition A12 typically includes salvage, repair, submarine depot and support, submarine tender, and missile support under "fleet auxiliary - medium" and includes icebreaker, miscellaneous replenishment (eg, oiler), and transport under "fleet auxiliary - large." Proposition A13 typically includes mine sweeping, lifting, rescue, and tug. Debris (A18) is included because of its occasional resemblance on radar scopes to boats and to submarine periscopes, snorkels, and antennas.

3.2 SPECIAL-CASE APPLICATION OF DEMPSTER'S RULE

Initial probability masses based on the number of each type of platform, the region, and the political/military situation can be estimated. Arbitrarily, we will assume these masses to be

$$\{m_1(Ai)\} = \{.003\ .013\ .04\ .03\ .04\ .02\ .04\ .06\ .02\ .015\ .012\ .09\ .03\ .01\ .13\ .07\ .02\ .007\}.$$

Other knowledge sources would correspond to the kinds of information derivable from sensor measurements and other observations. Examples of basic information available from a radar system are the following. Note that some of them require successive measurements.

- Radar range of initial detection. (Provides a measure of platform size).
- Location. (Merchants generally stay in merchant lanes, for example.)
- Operating speed. (Merchants tend to operate at intermediate speeds.)
- Lower bound of maximum speed. (A speed of 50 knots rules out most platform types and suggests a small, fast craft.)
- Speed changes. (Merchants generally do not vary their speed.)
- Course changes. (Merchants generally do not vary their course.)
- Projected destination.
- Miscellaneous maneuvers.

We immediately encounter two kinds of problems when attempting to translate these feature data categories into knowledge sources. First, some of the kinds of information are mutually dependent. Second, most of the features are time-oriented, and probability masses contributed earlier by a knowledge source may need to be discarded rather than combined with new data.

Delaying consideration of these problems, we consider first the simple case where we have a radar contact with an initial detection range and a single measurement of speed. To convert these measurements into probability masses, we employ a method similar to that used for emitter parameter distributions in [5]. For each measurement and each ship type, a strip corresponding to the measurement $\pm$ the average measurement error is overlaid on the appropriate distribution curve, figure 3-1 or figure 3-2, and the overlapped area is computed. (Figure 3-1 would be valid for only one antenna height, frequency, and environment state, and assumes a low signal strength; a family

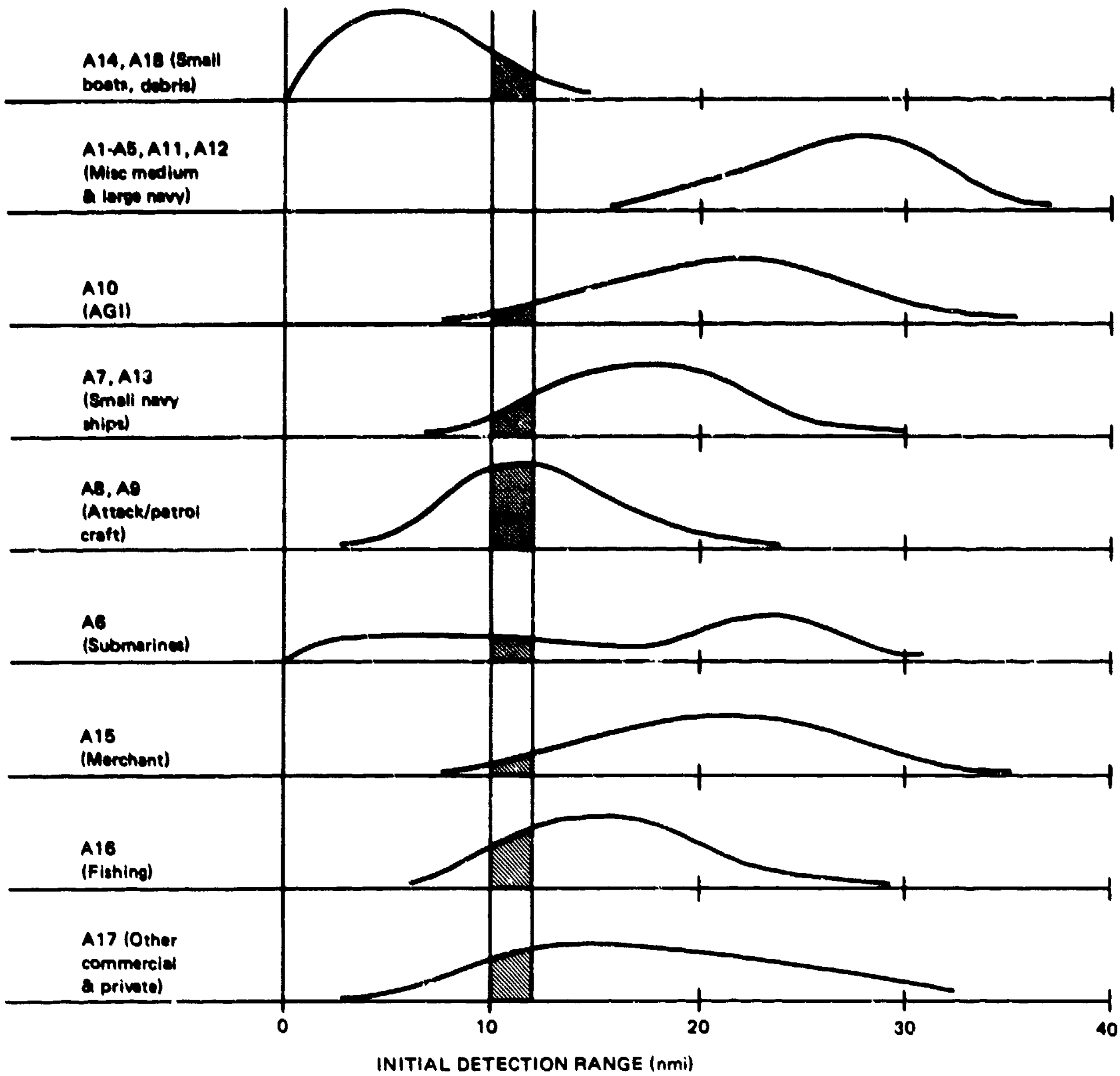

Figure 3-1. Distribution functions for initial detection range.

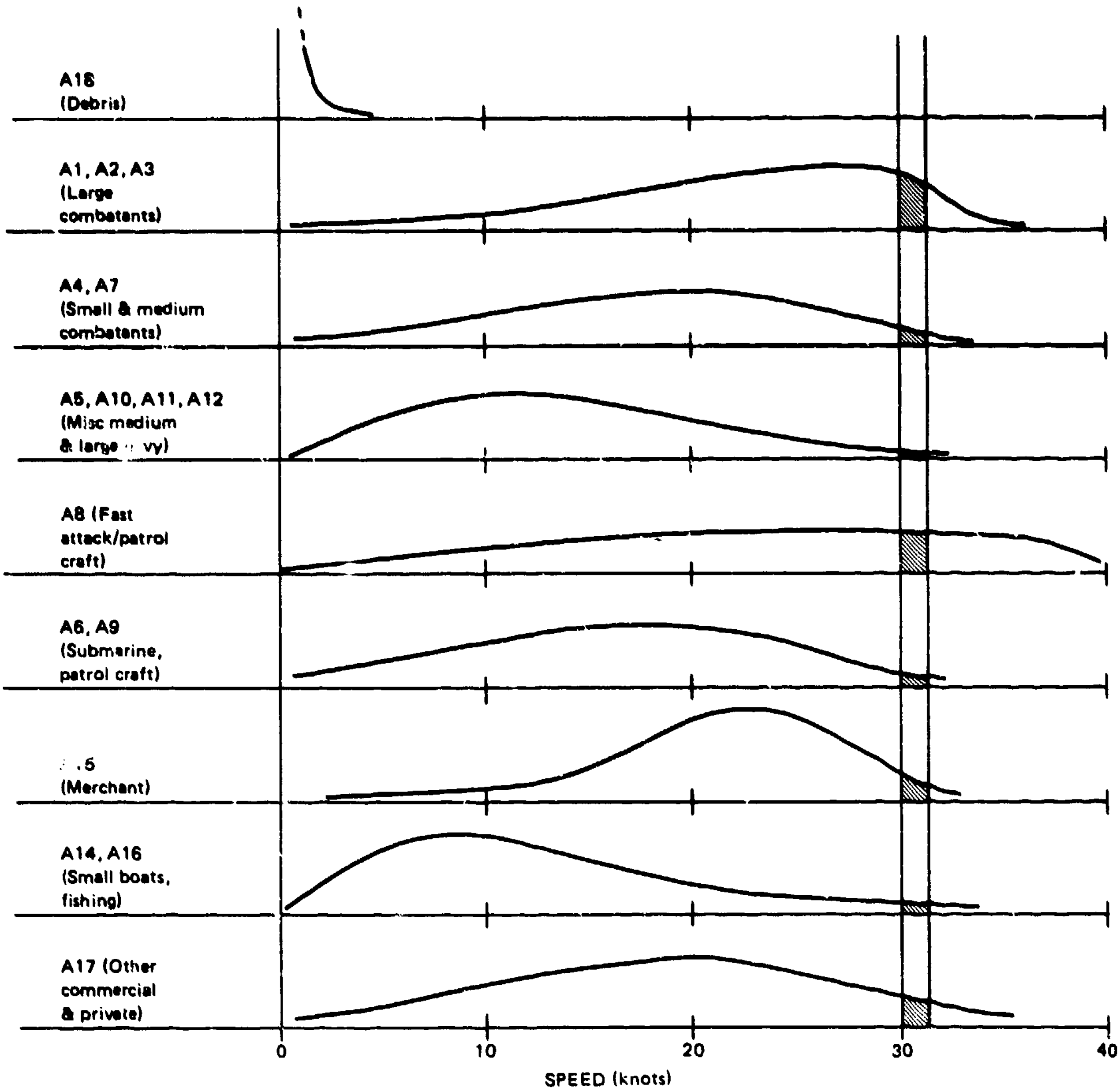

Figure 3-2. Distribution functions for speed.

of curves would be required.) These areas are normalized to sum to the complement of the probability mass of the uncertainty. In practice, the process could be automated by initially storing the mass vectors for incremented values of range and speed. Assuming an uncertainty mass of .3 for range and .4 for speed to represent our lack of confidence in the measurement and distribution functions, we have the following values of mass for range and speed.

$$\{m_2(Ai)\} = \{0\ 0\ 0\ 0\ 0\ .037\ .045\ .136\ .136\ .027\ 0\ 0\ .04\ .055\ .023\ .077\ .064\ .055\}$$

and

$$\{m_3(Ai)\} = \{.103\ .103\ .103\ .029\ .008\ .009\ .029\ .074.\ .009\ .008\ .008\ .008\ .008\ .011\ .034\ .011\ .045\ 0\}.$$

Using the special case of Dempster's rule (in Section 2.2) with m = 3, we have the combined masses

$$\{m(Ai)\} = \{.037\ .042\ .055\ .023\ .019\ .030\ .052\ .140\ .079\ .022\ .008\ .039\ .038\ .035\ .083\ .076\ .059\ .029\}$$

and

$$m(\theta) = .138.$$

3.3 IMPLEMENTATION IN A RULE-BASED SYSTEM

A number of platform identification rules are implemented in the rule-based system STAMMER2 [7]. The confidence mechanisms, based on MYCIN formulas [1], incrementally combine the support contributed for proposition A or $\tilde{}A$ about a contact. (The terminology is different, however, in that support for A and $\tilde{}A$ corresponds to belief in A and disbelief in A.) Examples of the kinds of rules implemented in STAMMER2 are the following.

Merchant Rules

1. If the contact's speed > 25, it is somewhat unlikely to be a merchant.

2. If the contact's speed < 9, it is somewhat unlikely to be a merchant.

3. If the contact changes speed, it is probably not a merchant.

4. If the contact changes course, it is probably not a merchant.

5. If the contact is not in a merchant lane, it is probably not a merchant.

6. If the contact's initial detection range < 16 and the radar signal is weak, it is somewhat unlikely to be a merchant.

7. If the contact is not within reach of any earlier sighted hostile, it is somewhat likely to be a merchant.

Submarine Rules

1. If the contact's initial detection range < 8 and its radar signal is strong, it is somewhat likely to be a submarine whose mode is surface.

2. If the contact's range < 3 and its speed > 3 and its radar signal is weak, it is likely to be a submarine whose mode is periscope/snorkel/antenna.

When two platform types are considered (eg, merchant and submarine), the two are performed independently. This approach becomes very unwieldy if more than a few types are considered and can easily lead to inconsistent conclusions. When a decision is to be made concerning a number of possible types, Dempster's rule is much more practical and consistent.

Merchant rules 1, 2, and 6 above should be replaced by the more comprehensive procedure described in Section 3.2, although this would sacrifice the appealing simplicity of the rules. Confidence computations for the other rules also can be handled with Dempster's rule if we assume that the kinds of evidence are sufficiently independent.

Suppose that the contact satisfies the conditions of Merchant Rules 4 and 5 and Submarine Rule 2. Recall that the types "submarine" and "merchant" correspond to propositions A6 and A15, respectively, in Section 3.1. (If we wished to, we could refine our frame of reference to include A6a and A6b, corresponding to submarine modes; however, this would create problems if the submarine does not remain in one mode.) We can introduce further sophistication to the rules by making the confidence in the conclusion a function of the parameters (eg, of the amount of course change). Whether or not we do this, assume that the contributions of mass from the three rules are

From MR4: $m_1(\tilde{}A15) = .3,\ m_1(\theta) = .7$
From MR5: $m_2(\tilde{}A15) = .25,\ m_2(\theta) = .75$
From S1: $m_3(A6) = .4,\ m_3(\theta) = .6.$

The three mass assignments can be combined simultaneously by using equations (2.24) through (2.27) with m = 3, or they can be combined in a pairwise fashion by using (2.20) through (2.23). In the latter case, the combining of m_1 and m_2 results also in a contribution of mass only to $\tilde{}A15$ and θ, and this is combined with m_3 in a manner similar to that used in the example shown in Figure 2-2.

Alternatively, we can compute the same results using a scheme devised by Barnett [10] for efficiently implementing Dempster's rule. When each knowledge source contributes mass only to θ and to either Ai or $\tilde{}$Ai for only one value of i (ie, when each confirms or denies just one of the n exclusive and exhaustive propositions), Barnett's scheme may be used to reduce computation time from exponential to linear. First, however, we need to coarsen our frame of discernment to avoid computing the support and plausibility for all $2^{18} - 1$

[10] Barnett JA.
Computational Methods for a Mathematical Theory of Evidence.
In Proc. IJCAI 7, Vol 2, pages 868-875. August, 1981.

= 262 143 general propositions. We can reduce n from 18 to 3 for this particular computation of Dempster's rule by letting our frame of discernment be the set of propositions:

P1 = A6

P2 = A15

P3 = ~(A6vA15).

Using Barnett's implementation in SIMULA (a general-purpose language), we have the combined masses:

m(P1) = m(A6) = .4

m(P2) = m(A15) = 0

m(~P2) = m(~A15) = .285

m(θ) = .315.

Translating back to our original 18 propositions, we have the following evidential intervals.

A6: [.4, 1]

A15: [0, .315]

and for the remaining 16 propositions (i ≠ 6, 15), we have

Ai: [0, .6].

3.4 CONVERSION OF USER'S WEIGHTS INTO MASSES

The "expert" or user who creates rules generally will give his weights in terms of support values s(B) instead of mass assignments. In some cases, m(B) will be equal to s(B)--for example, when B is one of the original n exclusive hypotheses--but often the intended probability masses will need to be computed. For example, the user might say, "I'm 60% sure it's not A3 and 70% sure it's not A17." These numbers sum to more than unity, so obviously we

cannot use them as probability masses. However, they can be interpreted as valid support values, and as such can easily be converted into the mass assignment: m[~(A3vA17)] = .6, m(~A17) = .1, and m(θ) = .3. This assignment used with equation (2.27) yields s(~A3) = .6 and s(~A17) = .7, the support values specified. Note that there is another support value implied by the user's assignments: s[~(A3vA17)] = .6.

For each assignment of mass probabilities, there is a unique set of support values, and for each (complete) set of support values, there is a unique mass assignment. The latter is given by Theorem 2.2 in [3] and as equation (2) in [10]. In our terminology, it is

$$m(A) = \sum_{B\&A=B} (-1)^{|a-b|}\, s(B) \tag{3.1}$$

where a and b are the sizes of A and B, respectively; ie, a is the count of all propositions Ai such that A&Ai = Ai and b is the count of all propositions Ai such that B&Ai = Ai.

With minimal training, the user can quickly convert his specified support values into a mass assignment. However, we would prefer to provide him and new users with a mechanism for automatic conversion. As illustrated above with an example, the support values specified by the expert can imply other support values. By letting all support values which are neither specified nor inferred be zero, we have the complete support specification intended by the expert. These are shown below for several cases. Using the complete support specification in equation (3.1) will result in the mass assignments shown. For the cases considered, the mass assignment can be quickly deduced from the specified values of support and equation (3.1) is satisfied but not needed.

Special Case

Expert's specification: The expert specifies support values for {Ak} where each Ak is an original proposition. In this case, the expert is specifying mass values, since $s(Ai) = m(Ai)$ for original propositions.

Complete support specification: For $B \neq \theta$, $s(B) = \sum s(Ak)$ where $B \neq \theta$ and the sum is over those Ak such that Ak is in {Ak} and $Ak\&B = Ak$. $s(\theta) = 1$. Note $s(B) = 0$ for every proposition B such that $B\&Ak = \tilde{}\theta$ for every k.

Mass assignment: $m(Ak) = s(Ak)$ for Ak in {Ak}, $m(\theta) = 1 - \sum s(Ak)$ where the sum is over Ak in {Ak}, and $m(B) = 0$ for $B \neq \theta$ or not in {Ak}.

Example: The expert specifies $s(A1) = .4$ and $s(A3) = .2$, where $n = 3$. The complete support specification is then $s(A1) = .4$, $s(A2) = 0$, $s(A3) = .2$, $s(\tilde{}A3) = .4$, $s(\tilde{}A1) = .2$, $s(\tilde{}A2) = .6$, and $s(\theta) = 1$. The mass assignment is $m(A1) = .4$, $m(A4) = .2$, $m(\theta) = .4$, and $m(B) = 0$ for every other proposition B.

One-General-Proposition Case

Expert's Specification: The expert specifies the support value $s(B')$, where B' is a general proposition.

Complete support specification: $s(B) = s(B')$ if $B \neq \theta$ and $B\&B' = B'$, $s(\theta) = 1$, and $s(B) = 0$ for every other proposition B.

Mass assignment: $m(B') = s(B')$, $m(\theta) = 1 - s(B')$, and $m(B) = 0$ for every other proposition B.

Example 1: The expert specifies $s(\tilde{}A1) = .3$, where $n = 18$. The complete support specification is then $s(\tilde{}A1) = .3$, $s(\theta) = 1$, and $s(B) = 0$ for every other proposition B. The mass assignment is $m(\tilde{}A1) = .3$, $m(\theta) = .7$, and $m(B) = 0$ for every other proposition B.

Example 2: The expert specifies $s(A1vA2) = .4$, where $n = 4$. The complete support specification is then $s(A1vA2) = s(\tilde{}A3) = s(\tilde{}A4) = .4$, $s(\theta) = 1$, and $s(B) = 0$ for every other proposition B. The mass assignment is $m(A1vA2) = .4$, $m(\theta) = .6$, and $m(B) = 0$ for every other proposition B.

Two-General-Proposition Case

Expert's specification: The expert specifies support values $s(B1) = s1$ and $s(B2) = s2$, where $s2 \geq s1$.

Complete support specification: $s(\theta) = 1$. For each proposition B such that $B \neq \theta$ and $B1\&B = B1$ or $B2\&B = B2$, $s(B) = s1$ if $B2\&B = \tilde{}\theta$, $s(B) = s2$ if $B1\&B = \tilde{}\theta$ or $B1\&B2 = B1$, and $s(B) = s1 + s2$ if $(BvB2)\&B = B1vB2 \neq B2$. For all others, $s(B) = 0$.

Mass assignment: If $B1\&B2 = \tilde{}\theta$, tnen $m(B1) = s1$, $m(B2) = s2$, and $m(\theta) = 1 - s1 - s2$; otherwise, $m(B1\&B2) = s1$, $m(B2) = s2 - s1$, and $m(\theta) = 1 - s2$. For all others, $m(B) = 0$.

Example 1: The expert specifies $s(\tilde{}A1) = .8$ and $s(A4) = .3$, where $n = 4$. In this case, it is considerably easier to first find the mass assignment, which is: $m(\tilde{}A1) = .5$, $m(A4) = .3$, and $m(\theta) = .2$. The complete support specification is $s(A4) = s(A1vA4) = s(A2vA4) = s(A3vA4) = s(\tilde{}A3) = s(\tilde{}A2) = .3$, $s(\tilde{}A1) = .8$, $s(\theta) = 1$, and $s(B) = 0$ for every other proposition B.

Example 2: The expert specifies $s(\tilde{}A1) = .7$ and $s(\tilde{}A2) = .8$, where $n = 18$. Again, it is easier to find the mass assignment, which is $m[\tilde{}(A1vA2)] = .7$, $m(\tilde{}A2) = .1$, $m(\theta) = .2$, and $m(B) = 0$ for every other proposition B. The complete support specification is $s(\tilde{}A1) = .7$, $s(\tilde{}A2) = .8$, $s[\tilde{}(A1vA2)] = .7$, $s(\theta) = 1$, and $s(B) = 0$ for every other proposition B.

4. TACTICAL PROBLEM FORMULATION

4.1 INTRODUCTION

Concern about accuracies or confidences arises in many different stages of analyses in the tactical situation assessment process. The problems tend to fall into two categories: (1) accuracies of estimates (eg, of position, velocity, and shipping density), and (2) confidences in hypotheses (eg, about platform identity and hostile intent). This effort addresses the latter category. We further confine our attention to sets of mutually exclusive hypotheses (or "propositions," as we are calling them) in order to use tractable confi ıce computing methods. We conjecture that sets of nonexclusive propositions currently handled by tactical analysts can be reformulated into a set or sets of exclusive propositions. The ultimate default is to form a set of two propositions (A and ~A) out of each proposition in the initial set. The next section gives examples of tactical problems expressed as sets of mutually exclusive propositions.

4.2 EX... ES OF MUTUALLY EXCLUSIVE PROPOSITIONS

<u>What Is It?</u>

Ai: The contact is type i.

Ai: . submarine is class i.

Ai: The underwater "swimmer" is type i.

(Types: frogman, commercial/pleasure diver, man overboard, man in small subsurface vehicle, subsurface robot or RPV, dolphin, fish, etc.)

Who Is It?

Ai: The contact is platform i.

This set is practical when there is considerable knowledge about what platforms could be in the region. An additional proposition usually needed is: The contact is not any of the platforms thought possibly to be in the region. Position information can rule out many of the platforms. Preferably, each platform i is "one-of-a-kind" in the region; ie, (1) known by name or hull number, or (2) the only one of that class, type or distinctive nature. This is not necessary, however; one can have an indistinguishable merchant #1 and merchant #2, for example.

This approach becomes more practical when the contact's type or class is known and only platforms of that type or class need be considered.

Whose Is It?

Ai: The contact's country of origin/registration is nation i.

This set is impractical as a pure, exhaustive set. A choice of friend, neutral, or hostile is a coarse alternative.

Which One Did It?

Ai: Radar contact i emitted the intercepted signal.

Ai: Surface contact i launched the helicopter.

For both, an additional proposition is: None of the contacts did it.

Which One Is It?

Ai: Current contact i is earlier contact X.

This is a "Contact Association" problem for the case where one set of exclusive propositions can be formulated about several current contacts. It requires eliminating possible duplicates; ie, disallowing contact j if it could be another detection of contact i.

Ai: Earlier contact i is current contact X.

This is a variation of the contact association problem which is useful when contact X is more fully identified than earlier contacts. The elimination of possible duplicates is more difficult than for the above case because of the difference in detection time of the earlier contacts.

When there is considerable knowledge about the platforms in the region and recent positions are held on all, this problem becomes the "Who is it?" problem above.

Ai: Current contact i is platform X.

This set is not very practical unless platform X is "one-of-a-kind." Use the contact association version if the last track of platform X is relevant.

For all three, an additional proposition is: None of these contacts is it. Also, the word "track" generally can be substituted for "contact."

Which Partitioning Is It?

Ai: Partitioning i of contacts is the correct partition.

Each partitioning is a collection of disjoint sets (each set representing a candidate track) whose union is the set of all contacts.

Where Is It?

Ai: The submarine is in section i.

Which Is Which?

A1: Contact 1 is platform X and Contact 2 is platform Y.

A2: Contact 1 is platform Y and Contact 2 is platform X.

This situation may be difficult to automatically identify. For k contact and platforms, there will be k! propositions. As k increases, this formulation of the problem becomes increasingly impractical in a rule-based system.

Is It or Isn't It?

(ie, true or false?)

Contact X is the same platform as contact Y.

The contact is a merchant.

The contact is hostile.

The contact is a combatant.

The platform is preparing to attack.

The hostile submarine is in innocent passage.

The (simple) event reported in message A is the same (simple) event reported in message B.

4.3 DEPENDENCIES AMONG SETS OF PROPOSITIONS

We see from the sets of propositions in section 4.2 that some questions about a contact are not independent of other questions. For example, associating a new contact with an earlier sighted platform whose type is known contributes to the confidence that the new contact is that type. Conversely, observing that the new contact has structural or behavior attributes consistent with the type of the earlier sighted platform increases the confidence in associating the two. In general, the computation of masses for two sets of propositions (in this example, the set for type and the set for contact association) frequently will share some of the same evidence, in which case the resulting mass assignments for one set must not be used in the computation of the other. The lesson is that the computation processes for two sets of propositions should share any evidence pertinent to both but should not use each other's output.

Computations for two sets of propositions may occasionally give contradictory results (eg, contact 3 is probably platform X but platform X is a cruiser and contact 3 is probably a frigate) because of contradictory evidence and the many uncertainties involved. If contradictory results occur regularly, this is probably a warning that the "knowledge sources" need improvement in their conversion of raw data into mass assignments.

5. THE CONTACT ASSOCIATION PROBLEM

5.1 INTRODUCTION

Here we address the several kinds of contact association problems outlined in Section 4. We assume that detection data from the various sensors have already been preprocessed and correlated to the degree feasible with a multisensor correlator-tracker scheme. However, the contact association problem of primary interest here is that where detections of contact X have ceased for a while, and for these cases, an alternative to using algorithmic correlation initially is to use simple inference rules which eliminate obviously impossible pairings of contacts; eg, those requiring impossible speeds or in conflict because of a difference in observed type of class. Further elimination of impossible pairings can be made by using logical rules such as those in PTAPS (Platform-Track Association Production Subsystem [11] [12] [13]). For example, if earlier contact X is the only unaccounted-for platform of some known type of class and one of the current contacts is known to be that same type or class, the PTAPS rules will operate to match the two and eliminate all other pairings for contact X (in this case also eliminating the association problem for contact X).

5.2 AN EXAMPLE OF "WHICH ONE IS IT?"

In figure 5-1, an example is given of the contact association problem where exclusive propositions can be formulated about which current contact is

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[11] Dillard RA.
Higher Order Logic for Platform Identification in a Production System.
Technical Document 288, Naval Ocean Systems Center, October 17, 1979.

[12] Dillard RA.
Experimental Tests of PTAPS Performance in Three Types of Production System Structures.
Technical Document 385, Naval Ocean Systems Center, September 17, 1980.

[13] Dillard RA.
A Platform-Track Association Production Subsystem.
In Proceedings of the Fourth MIT/ONR Workshop on Command and Control. June, 1981.

Propositions

A1: Current contact 1 is earlier contact X.
A2: Current contact 2 is earlier contact X.

An-1: Current contact n-1 is earlier contact X.
An: No current contact is contact X.

Assumptions

1. Propositions A1 through An are exclusive and exhaustive.
2. Contact X is a surface ship whose type is known.
3. Position data are available for all contacts.

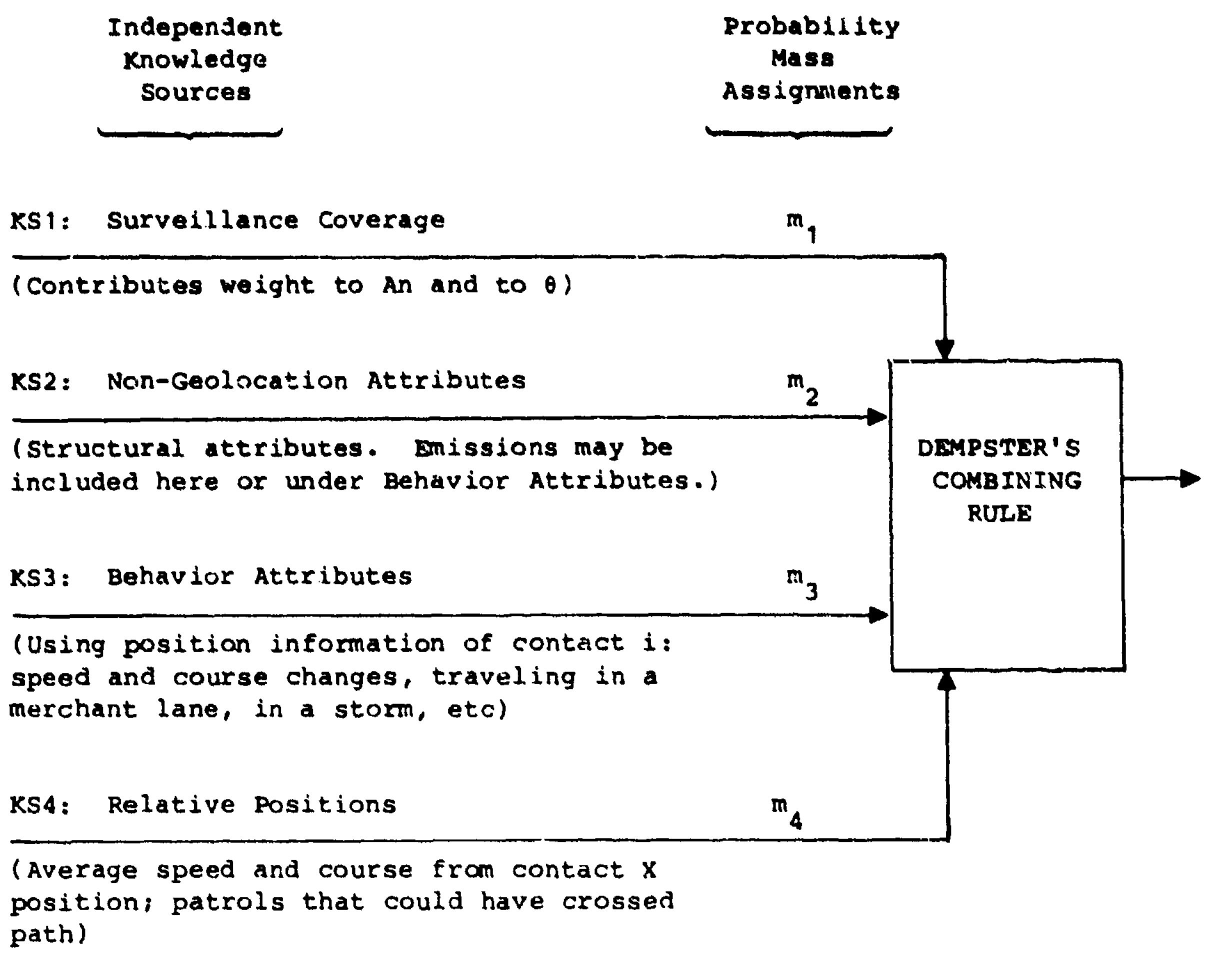

Figure 5-1. Example of a contact association problem.

the earlier contact X and where the type of contact X is known. In this example, we assume that the impossible pairs have been eliminated and the remaining contacts have been numbered from 1 to n-1. "An" is the proposition that none of these n-1 current contacts is contact X. [If it concludes that there are no possible pairs, the procedure halts with the conclusion m(An) = 1.]

An initial knowledge source KS1 provides probability masses of An and θ. KS1 represents knowledge about the degree of surveillance coverage in the region. The knowledge sources KS2, KS3, and KS4 each represent the interpretation of combined pieces of raw data. Appropriate algorithms and combining methods are needed to generate the mass assignments m2, m3, and m4. (In a rule-based system, rules would control the assignment process.) The assignment of mass to θ by each should derive from the uncertainty of the correctness of the data and its interpretation. (If there is no evidence for KSj, then mj(θ) = 1 and no combining for KSj is needed.)

Unless it is certain that one of the contacts is contact X, knowledge sources KS2, KS3, and KS4 should contribute mass to An. The mass m_j(An) generally should be large if that knowledge source indicates that none of the contacts matches contact X very well, judged by the evidence. The probability masses m_j(Ai) for i = 1, ..., n-1 are derived by normalizing the computed measures of match (based on KSj evidence) to sum to 1 - m_j(An) - $m_j(\theta)$. The process of computing the measures of match would vary with the knowledge source and, as mentioned above, would be controlled by rules in a rule-based system.

An output of Dempster's combining rule in figure 5-1 is the set of evidential intervals [s(Ai), p(Ai)].

5.3 CONSIDERATIONS WHEN INTERFACING TECHNIQUES

The combining process described in the previous section begins when the algorithmic correlator-tracker scheme (alternatively, a ruleset for initial

contact selection) has associated or disassociated contacts with near certainty; and unless some of the evidence contributes probability mass to one or more general propositions concerning the contacts, the process defaults to a Bayesian one. Typically, these general propositions would be θ (representing uncertainty about the evidence and its interpretation) and $\sim$Ai (NOT Ai, where Ai is the proposition that contact i and contact X are the same platform). For example, the bearing of an intercepted signal may be correlated only with contact 3 but the emitter type is not carried by contact X. Based on this evidence, mass totaling unit would be assigned to $\sim$Ai and θ, desirably with the proportion depending largely on the likelihood that contact i indeed emitted the signal. As another example, suppose that for contact 4 to be the same platform as contact X, the platform would have had to change course and/or speed in a manner uncharacteristic of its type. The general proposition $\sim$A4 should then be assigned mass. An example of another kind of general proposition is when observations of ship profile show contacts 2 and 3 to be the same type of platform as contact X. The mass assigned to A2vA3 should be small if many ships of that type are in the region but near unity if only two could be there. Mechanisms for doing this would be fairly simple to implement in a rule-based system.

Note in the above examples that some of the raw data underlying the evidence may also have been used in the initial correlation algorithms, especially since a number of correlation schemes use ESM and nongeolocation data [14] [15]. If the data have been used by the correlation system in a sufficiently optimum manner, the later combining stage should not also use it but should instead use the correlator output as evidence (combining it with any other independent evidence). The primary reasons why some data may be better

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[14] Goodman IR, Wiener HL and Willman WW.
Naval Ocean-Surveillance Correlation Handbook, 1979.
Report 8402, Naval Research Laboratory, September 17, 1980.

[15] Goodman IR.
Applications of Possibility Theory to Ocean Surveillance Correlation.
In Proc. 48th Military Operations Research Society Meeting. December, 1981.

utilized at the mass combining stage are (1) they support a general proposition; (2) the interpretation is subject to change with the situation; and (3) conversion of the raw data into evidence is more easily implemented with rules. In a rule-based system, the initial correlation process may serve only to trigger the mass-combining stage of contact association, and the "knowledge sources" would formulate evidence out of the raw data in a more complete manner.

The ideal formulation of the contact association problem is that of partitioning the contacts into candidate tracks. Because of the factorial growth of computation and storage requirements, this approach is currently feasible only in a low-density target environment. Since Dempster's combining process can impose an exponential growth in addition, another algorithmic process would first be needed to eliminate all but the most likely partitionings.

6. EXPERIMENTAL RESULTS AND CONCLUSIONS

Initial experiments in STAMMER and in ROSIE employed a set of rules which contribute confidences concerning platform type. Two of the rules assign masses according to the scheme outlined in Section 3.2 for initial detection range and speed, respectively. Algorithms for computing Dempster's rule were implemented for (1) the special case of combining discussed in Section 2.2; (2) the combining of masses $m_j(\tilde{}Ai)$ and $m_j(\theta)$ for a single value of i; and (3) the combining of the results of (1) and (2). The combining was accomplished with procedure rulesets and function rulesets in ROSIE and with oracle-like functions in Interlisp code in STAMMER. Oracles are computation functions used in STAMMER rule conditions in much the same way as relational assertions. In this combining application, however, the oracles are called as actions.

Typescripts of the experiments in ROSIE and in STAMMER2 are given in appendices I and II, respectively. In the ROSIE version, the mass combining results are presented as "pro-con" pairs rather than as evidential intervals; ie, the complement of the plausibility is presented rather than the plausibility. This form of presentation seems to convey more immediately a meaningful measure of evidence against a proposition. In the STAMMER2 version, the "most likely" type is listed. The measure used is $m(Ai) + p(Ai) - 1$; ie, the support for Ai minus the support for $\tilde{}Ai$, which ranges from -1 to 1. In both systems, the mass assignments resulting from the firing of rules were stored in such a way that they could be selectively "recalled" if later information warrants.

Although computational limitations presently constrain us in the assignment of probability masses, we find the results encouraging. Future plans include experimenting with other kinds of tactical hypotheses, designing computational schemes for less constrained cases of Dempster's rule, and designing mechanisms for explaining the assignment and computing of confidences. We also need to implement the combining of dependent evidence, along with the combining by Dempster's rule. For this, we can begin with the dependency graph approach described in [5] but we will need to find a way of automatically modifying the graph as the user adds and modifies rules. Priority

will be given to the design of confidence-combining features essential to a system whether or not it is frequently subject to user modification, and attention will be given later to user modification problems.

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Report 8402, Naval Research Laboratory, September 17, 1980.

[15] Goodman IR.
Applications of Possibility Theory to Ocean Surveillance Correlation.
In Proc. 48th Military Operations Research Society Meeting. December, 1981.

APPENDIX I: TYPESCRIPT OF AN EXPERIMENT IN ROSIE

```
                    TM
          [ Rosie     Version 1.3  21-Jul-82  11:59:09 ] *

<2> load ir-rosie.
To READ-REPORT
To RUN_TYPE_RULES of CURRENT-TRACK on CURRENT-REPORT
To generate SUBTENDED_ANGLE of LATLONS
To generate ABS_VALUE of NUMBERC
To generate TIME_DIFFERENCE of TIMES
To generate TIME_DELTA of REPORTS
To generate DISTANCE of REPORTS
To generate MIN_SPEED of REPORTS
To generate DIRECTION of LATLONS
To generate COURSE-SPEED_CHANGE of REPORTS
To generate PLATFORM_TYPE of TRACK
To generate COURSE_DIFFERENCE of COURSES
To generate RANGE-TO-LANE-CENTER of POSITION to LANE
To generate REPORT_COUNT of TRACK
To generate FIRST-REPORT in TRACK
To generate LAST-REPORT in TRACK
To decide PLATFORM is a high-value-target
To decide PLATFORM does carry_missiles
To ASSIGN-TYPE-CONFIDENCES for TRACK of EVIDENCE-DATA to TYPE-CHOICES
To generate CONFIDENCE-SET of TRACK
To generate MASS-VECTOR_DERIVED from SENSOR-MEASUREMENT
To generate ALL-TYPE-VECTORS in CONF-SET
To generate SINGLE-TYPE-NEGS in CONF-SET
To generate VECTOR-CONVERSION for PLAT-CHOICES from WEIGHTS
To decide MEMBERX is not_present
To GIVE_TYPE-MASSES for TRACK
To generate COMBINED-NEG-SINGLES of NEG-CHOICES
To generate SIMPLE-DEMPSTER-COMBINATION of MASS-VECTORS
To LIST_CONFIDENCES over PRO-CON-PAIRS
To generate PRO-CON-PAIRS from MASSES
To generate TUPLE-SUM of TUPLEX over LENGTHX
To generate PAIR-COMBINATION of VECTOR1 with VECTOR2
To generate MIXED-COMBINATION of ALL-VECTOR with NEG-SINGLE
To TELL about ARG

To receive the first report, type:    go read-report.

To see evidential conclusions about platform-type for a
track, type:  go give-type-masses for track #<integer>.

For an explanation of a rule type:
       go tell about [rule-name].
```

---

*ROSIE is a registered trademark of the Rand Corporation, from which the software is licensed.

<3> go give_type-masses for track #1.

There has been no useful evidence yet concerning that track.
The following masses are based on a priori probabilities.

Platform Types: Pro-Con Masses

CARRIER: <.003, .647>
CRUISER: <.013, .637>
DESTROYER: <.04, .61>
FRIGATE: <.03, .62>
AMPHIBIOUS: <.04, .61>
SUBMARINE: <.02, .63>
SMALL-FIGHTING-SHIP: <.04, .61>
FAST-ATTACK/PATROL-CRAFT: <.06, .59>
PATROL-CRAFT: <.02, .63>
INTELL-COLLECTOR: <.015, .635>
SURVEY/RESEARCH: <.012, .638>
FLEET-AUXIL-MED/LRG: <.09, .56>
FLEET-AUXIL-SMALL: <.03, .62>
SMALL-BOAT: <.01, .64>
MERCHANT: <.13, .52>
FISHING: <.07, .58>
OTHER-COMMER/PRIVATE: <.02, .63>
DEBRIS: <.007, .643>

<4> go read-report.
REPORT #1 is a report of a new track: TRACK #1
Source: RADAR
Time: 261110
latitude: -7.3
longitude: 71.729
range: 11.3
course: 90

* * * Platform-Type Rules activated * * *

Radar-Popup-Range Rule fires for TRACK #1. (Range = 11.3)

Not-Known-Hostile Rule fires:
The position of the first-report of TRACK #1 is not
within reach of any platform identified as hostile.

Outside-All-Lanes Rule fires:
The position of REPORT #1 of TRACK #1 is outside all merchant lanes.

To receive the next report, type: go read-report.

<5> go tell about radar-popup-range.

The initial radar detection range is indicative of the platform's size and contributes confidence weights over all platform types.

<6> go tell about not-known-hostile.

If no earlier sighted hostile could have reached the position of the new contact, then the contact is probably commercial or private: merchant (.2), fishing (.1), other-commer/private (.1).

<7> go tell about outside-all-lanes.

If the sighting is outside of all merchant lanes, then the ship might not be a merchant. (.3).

<8> report #1?
[REPORT #1]
    REPORT #1 is a report.
    REPORT #1 is a report of TRACK #1.
    REPORT #1 is a last-report of TRACK #1.
    REPORT #1 is a first-report of TRACK #1.
    RADAR is a source of REPORT #1.
    261110 is a time of REPORT #1.
    -7.3 is a latitude of REPORT #1.
    71.729 is a longitude of REPORT #1.
    11.3 is a range of REPORT #1.
    90 is a course of REPORT #1.
    REPORT #1 is a radar-popup.

<9> track #1?
[TRACK #1]
    CONFIDENCE-SET #1 is a confidence-set of TRACK #1.
    TRACK #1 is a track.
    REPORT #1 is a report of TRACK #1.
    REPORT #1 is a last-report of TRACK #1.
    REPORT #1 is a first-report of TRACK #1.
    RADAR-POPUP-RANGE is a fired-rule of TRACK #1.
    NOT-KNOWN-HOSTILE is a fired-rule of TRACK #1.
    OUTSIDE-ALL-LANES is a fired-rule of TRACK #1.

<10> confidence-set #1?
[CONFIDENCE-SET #1]
    CONFIDENCE-SET #1 is a confidence-set.
    CONFIDENCE-SET #1 is a confidence-set of TRACK #1.
    <<.003, .013, .04, .03, .04, .02, .04, .06, .02, .015, .012,
    .09, .03, .01, .13, .07, .02, .007>, <0, 0, 0, 0, 0, 0, .037, .045
    , .136, .136, .027, 0, 0, .045, .055, .023, .077, .064, .055>,
    <0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, .2, .1, .1, 0>> is

```
    an all-type-vectors in CONFIDENCE-SET #1.
    <<MERCHANT, .3>> is a single-type-negs in CONFIDENCE-SET #1.

<11> go give_type-masses for track #1.

   Platform Types:      Pro-Con Masses

CARRIER:      <.001404559, .8347303>
CRUISER:      <.006086421, .8300484>
DESTROYER:      <.01872745, .8174074>
FRIGATE:      <.01404559, .8220892>
AMPHIBIOUS:      <.01872745, .8174074>
SUBMARINE:      <.03072862, .8054062>
SMALL-FIGHTING-SHIP:      <.04611634, .7900185>
FAST-ATTACK/PATROL-CRAFT:      <.1151114, .7210234>
PATROL-CRAFT:      <.08789416, .7482407>
INTELL-COLLECTOR:      <.02240271, .8137321>
SURVEY/RESEARCH:      <.005618235, .8305166>
FLEET-AUXIL-MED/LRG:      <.04213676, .7939981>
FLEET-AUXIL-SMALL:      <.0407322, .7954026>
SMALL-BOAT:      <.03558215, .8005527>
MERCHANT:      <.1111224, .7741719>
FISHING:      <.1244283, .7117065>
OTHER-COMMER/PRIVATE:      <.08134996, .7547849>
DEBRIS:      <.03392009, .8022147>


<12> go read-report.
REPORT #2 is another report of the track:  TRACK #1
  Source:  RADAR
  Time:  261120
  latitude:  -7.3
  longitude:  71.815
  range:  5.7
  speed:  31
  course:  90

      * * *  Platform-Type Rules activated  * * *


Speed Rule fires for TRACK #1.   (Speed = 31)


To receive the next report, type:  go read-report.

<13> go tell about speed.

The speed measurement contributes confidence weights over all
platform types.
```

```
<14> confidence-set #1?
[ CONFIDENCE-SET #1 ]
    CONFIDENCE-SET #1 is a confidence-set.
    CONFIDENCE-SET #1 is a confidence-set of TRACK #1.
    <<.003, .013, .04, .03, .04, .02, .04, .06, .02, .015, .012,
    .09, .03, .01, .13, .07, .02, .007>, <0, 0, 0, 0, 0, .037, .045
    , .136, .136, .027, 0, 0, .045, .055, .023, .077, .064, .055>,
    <0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, .2, .1, .1, 0>, <
    .103, .103, .103, .029, .008, .009, .029, .074, .009, .008,
    .008, .008, .008, .011, .034, .011, .045, 0>> is an
    all-type-vectors in CONFIDENCE-SET #1.
    <<MERCHANT, .3>> is a single-type-negs in CONFIDENCE-SET #1.

<15> go read-report.
REPORT #3 is another report of the track:  TRACK #1
  Source:  RADAR
  Time:  261130
  latitude:  -7.227
  longitude:  71.857
  range:  5.0
  speed:  30
  course:  30

      * * *  Platform-Type Rules activated  * * *


Course-Changed Rule fires for TRACK #1:
 REPORT #3 course:  30
 REPORT #1 course:  90


To receive the next report, type:  go read-report.

<16> go tell about course-changed.

If the course has changed significantly, then the ship
probably isn't a merchant (.6).

<17> confidence-set #1?
[ CONFIDENCE-SET #1 ]
    CONFIDENCE-SET #1 is a confidence-set.
    CONFIDENCE-SET #1 is a confidence-set of TRACK #1.
    <<.003, .013, .04, .03, .04, .02, .04, .06, .02, .015, .012,
    .09, .03, .01, .13, .07, .02, .007>, <0, 0, 0, 0, 0, .037, .045
    , .136, .136, .027, 0, 0, .045, .055, .023, .077, .064, .055>,
    <0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, .2, .1, .1, 0>, <
    .103, .103, .103, .029, .008, .009, .029, .074, .009, .008,
    .008, .008, .008, .011, .034, .011, .045, 0>> is an
    all-type-vectors in CONFIDENCE-SET #1.
    <<MERCHANT, .3>, <MERCHANT, .6>> is a single-type-negs in
    CONFIDENCE-SET #1.
```

```
<18> go read-report.
REPORT #4 is another report of the track:  TRACK #1
  Source:  EW
  Time:  261132
  latitude:  -7.2917
  longitude:  71.9
  emitter:  SQUARE-TIE-RADAR
  bearing:  330

      * * *  Platform-Type Rules activated  * * *


Square-Tie-Radar Rule fires for TRACK #1.


To receive the next report, type:  go read-report.

<19> go tell about square-tie-radar.

If the intercepted signal is a square tie radar, the contact is
likely to be a fast-attack/patrol-craft (.4) or a small-fighting-
ship (.2).

<20> track #1?
[ TRACK #1 ]
    CONFIDENCE-SET #1 is a confidence-set of TRACK #1.
    TRACK #1 is a track.
    REPORT #1 is a report of TRACK #1.
    REPORT #2 is a report of TRACK #1.
    REPORT #3 is a report of TRACK #1.
    REPORT #4 is a report of TRACK #1.
    REPORT #4 is a last-report of TRACK #1.
    REPORT #1 is a first-report of TRACK #1.
    RADAR-POPUP-RANGE is a fired-rule of TRACK #1.
    NOT-KNOWN-HOSTILE is a fired-rule of TRACK #1.
    OUTSIDE-ALL-LANES is a fired-rule of TRACK #1.
    SPEED is a fired-rule of TRACK #1.
    COURSE-CHANGED is a fired-rule of TRACK #1.
    SQUARE-TIE-RADAR is a fired-rule of TRACK #1.

<21> confidence-set #1?
[ CONFIDENCE-SET #1 ]
    CONFIDENCE-SET #1 is a confidence-set.
    CONFIDENCE-SET #1 is a confidence-set of TRACK #1.
    <<.003, .013, .04, .03, .04, .02, .04, .06, .02, .015, .012,
    .09, .03, .01, .13, .07, .02, .007>, <0, 0, 0, 0, 0, .037, .045
    , .136, .136, .027, 0, 0, .045, .055, .023, .077, .064, .055>,
    <0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, .2, .1, .1, 0>, <
    .103, .103, .103, .029, .008, .009, .029, .074, .009, .008,
    .008, .008, .008, .011, .034, .011, .045, 0>, <0, 0, 0, 0, 0, 0
    , .2, .4, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0>> is an all-type-vectors
    in CONFIDENCE-SET #1.
```

```
<<MERCHANT, .3>, <MERCHANT, .6>> is a single-type-negs in
CONFIDENCE-SET #1.

<22> go give_type-masses for track #1.
Running in To generate TUPLE-SUM of TUPLEX over LENGTHX rule 2, , Load
 11.75
 Used 151.219 compute-seconds, 95.885 gc-seconds, with 6953 page faults

   Platform Types:      Pro-Con Masses

CARRIER:      <.02636711, .8753503>
CRUISER:      <.02989827, .8718191>
DESTROYER:      <.03943236, .862285>
FRIGATE:      <.01616047, .8855569>
AMPHIBIOUS:      <.01342259, .8882948>
SUBMARINE:      <.02105637, .880661>
SMALL-FIGHTING-SHIP:      <.1043268, .7973906>
FAST-ATTACK/PATROL-CRAFT:      <.2982748, .6034426>
PATROL-CRAFT:      <.0561144, .845603>
INTELL-COLLECTOR:      <.01567102, .8860464>
SURVEY/RESEARCH:      <.005402734, .8963147>
FLEET-AUXIL-MED/LRG:      <.02774377, .8739736>
FLEET-AUXIL-SMALL:      <.0268845, .8748329>
SMALL-BOAT:      <.02463102, .8770864>
MERCHANT:      <.03126466, .9412162>
FISHING:      <.07938432, .8223331>
OTHER-COMMER/PRIVATE:      <.06533772, .8363797>
DEBRIS:      <.0203445, .8813729>


<23> go read-report.

There are no more reports.
<24> info storage.
Collecting...

 TYPE                                  USED     ASSIGNED
ARRAYP       arrays                    12265    21504
STACK        stack, swap buffer        14848    14848
SWPARRAYP    swap array handles        204      512
STACKP       stack pointers            1        512
GC.BTAB      gc bittable               3584     3584
ATOM.HASH    atom hash table           1024     1024
LISTP        lists                     40814    51712
VCELLP       value cells               217      1024
LITATOM      atoms                     7059     8192
FLOATP       floating numbers          86       512
FIXP         large numbers             1109     3072
STRINGP      string pointers           529      1024
ATOM.CHARS   atom name characters      7227     7680
STRING.CHARS string characters         2223     3072
```

```
FRAME         FRAMEs                      484     512
        SUM (9 pages left)               91674   118784

<25> logout.
```

APPENDIX II: TYPESCRIPT OF AN EXPERIMENT IN STAMMER2

```
[PHOTO:  Recording initiated  Wed 8-Sep-82 12:53PM]

[Link from DILLARD, TTY 323]

 TOPS-20 Command processor 4(560)
@<NOSCAI.STAMMER>STAMMER2
Type (STAMMER) to begin.
(<NOSCAI.STAMMER>STAMMER2.EXE.1 . <LISP>LISP.EXE.145)
_LOAD(STAM-CONF)
FILE CREATED  8-Sep-82 12:31:49
IR-STAMCOMS
(IMPLIESASRT redefined)
(CONSTRUCT redefined)
(ROUGHLY-THE-SAME-COURSE-AS redefined)
(new QHPRODS property for <WHATFORM>)
<DILLARD>STAM-CONF..5
_(STAMMER)
Welcome to version 2.5 of the STAMMER TSA system.
Memory file? (Default is MEMORY.): STAM-MEMORY
Memory initialized.
Rulefile? (Default is RULES.):IR-STAM-RULES
Rules loaded
What file would you like to take messages from?
(Default is SCENE.ICE): IR-STAM-MSGFILE

Are you running on a Tektronix?No
Do you have a Tektronix available for display? No

     RADAR contact at (-7.3 71.729)  Time: 10
     Associated with track CONTACT1

A0201: Updating belief mass assigned to association of
CONTACT1, RANGE, and 11.32825.
A0209: Updating belief mass assigned to association of
CONTACT1, MERCHANT, and -.3.
A0204: CONTACT1 is  a UNIDENTIFIED.
A0173: Updating belief mass assigned to association of
CONTACT1, (MERCHANT FISHING OTHER-COMMER/PRIVATE), and (.2 .1 .1).
A0171: CONTACT1 is  a RADAR-CONTACT.
Question?  WHY is A0173
STAMMER applied the rule(s)
NOT-KNOWN-COMBATANT
Question?  PRINT the rule NOT-KNOWN-COMBATANT
If the contact could not be any earlier sighted combatant, then it
may be a merchant, fishing boat, or other commercial or private
ship (.2, .1 .1).
Question?  WHY is A0201
STAMMER applied the rule(s)
DETECTION-RANGE
```

Question? PRINT the rule DETECTION-RANGE
The initial radar detection range is indicative of the platform's size, and contributes confidence weights over all platform types.
Question? WHY is A0209
STAMMER applied the rule(s)
OUTSIDE-ALL-LANES
Question? PRINT the rule OUTSIDE-ALL-LANES
If a sighting is outside all merchant lanes, then the vessel might not be a merchant. (.3)
Question? WHAT IS THE INFERRED-TYPE OF CONTACT1

Type:	Support	Plausibility
CARRIER:	.001404557	.1652697
CRUISER:	.006086421	.1699516
DESTROYER:	.01872745	.1825926
FRIGATE:	.01404559	.1779108
AMPHIBIOUS:	.01872745	.1825926
SUBMARINE:	.03072862	.1945938
SMALL-FIGHTING-SHIP:	.04611634	.2099815
FAST-ATTACK/PATROL-CRAFT:	.1151114	.2789766
PATROL-CRAFT:	.08789416	.2517593
INTELL-COLLECTOR:	.02240271	.1862679
SURVEY/RESEARCH:	.005618234	.1694834
FLEET-AUXIL-MED/LRG:	.04213676	.2060019
FLEET-AUXIL-SMALL:	.0407322	.2045974
SMALL-BOAT:	.03558215	.1994473
MERCHANT:	.1111224	.2258281
FISHING:	.1244283	.2882935
OTHER-COMMER/PRIVATE:	.08134996	.245215l
DEBRIS:	.03392009	.1977853

The most likely type is FISHING.

I don't know.
Question? Quit
Leaving EXPLAIN

RADAR contact at (-7.3 71.815) Time: 20
Associated with track CONTACT1

A0233: FIRED is a SPEED-RULE of CONTACT1.
A0234: Updating belief mass assigned to association of CONTACT1, SPEED, and 30.70887.
Question? WHY is A0234
STAMMER applied the rule(s)
SPEED2
Question? PRINT the rule SPEED2
The speed measurement contributes confidence weights over all platform types.
Question? WHAT IS THE INFERRED-TYPE OF CONTACT1

Type:	Support	Plausibility
CARRIER:	.03375717	.159586
CRUISER:	.03827802	.1641068
DESTROYER:	.05046431	.1763131
FRIGATE:	.02068985	.1465187
AMPHIBIOUS:	.01718462	.1430134
SUBMARINE:	.02695795	.1527868
SMALL-FIGHTING-SHIP:	.04710176	.1729306
FAST-ATTACK/PATROL-CRAFT:	.1280225	.2538513
PATROL-CRAFT:	.07184189	.1976707
INTELL-COLLECTOR:	.02006322	.145892
SURVEY/RESEARCH:	.006916988	.1327458
FLEET-AUXIL-MED/LRG:	.03551967	.1613485
FLEET-AUXIL-SMALL:	.03441957	.1602484
SMALL-BOAT:	.0315345	.1573633
MERCHANT:	.1000685	.1881486
FISHING:	.1016338	.2274626
OTHER-COMMER/PRIVATE:	.08365029	.2094791
DEBRIS:	.02604656	.1518754

The most likely type is FAST-ATTACK/PATROL-CRAFT.

I don't know.
Question? Quit
Leaving EXPLAIN

RADAR contact at (-7.227 71.857) Time: 30
Associated with track CONTACT1

A0257: Updating belief mass assigned to association of CONTACT1, MERCHANT, and -.6.
Question? WHY is A0257
STAMMER applied the rule(s)
COURSE-CHANGED
Question? HOW does rule COURSE-CHANGED apply to A0257
The rule was applied with the assertions

A0171: CONTACT1 is a RADAR-CONTACT.

A0221: SIGHTING5 is a sighting of CONTACT1.

A0235: SIGHTING5 is other than a last sighting of its platform.

A0254: SIGHTING7 is the successor (in time) of SIGHTING5.

A0249: EW is not known to be the source of SIGHTING7.

A0229: 90.0 is the course of SIGHTING5.

A0255: 29.71294 is the course of SIGHTING7.

A0256: 29.71294 is not roughly the same course as 90.0.

```
Question?  PRINT the rule COURSE-CHANGED
If the course has changed significantly, then the sighting may
  not be a merchant. (.6)
Question?  Quit
Leaving EXPLAIN

     Passive detection. Heard SQUARE-TIE at bearing 330  Time: 32
     Associated with track CONTACT1

Report: CONTACT1 carries anti-ship cruise missiles
and is using a fire-control radar in the direction of ownship.
A0281: *Carries anti-ship missiles* is  a FREEFORM-INFERENCE of CONTACT1
.
A0280: *USSR or a friend of USSR* is  a FREEFORM-INFERENCE of CONTACT1.
A0279: Updating belief mass assigned to association of
CONTACT1, (SMALL-FIGHTING-SHIP FAST-ATTACK/PATROL-CRAFT), and (.2 .4).
A0278: CONTACT1 is MIL-BATTLE.
A0277: The medium of CONTACT1 is SURFACE.
A0170: CONTACT1 is  a EW-CONTACT.
Question?  WHY is A0279
STAMMER applied the rule(s)
SQUARE-TIE-RADAR1
Question?  PRINT the rule SQUARE-TIE-RADAR1
If the intercepted signal is a Square Tie radar, the contact is a
  missile-bearing fast-attack craft or small ship and is from USSR or a
  friend of USSR.
Question?  PRINT the rule SQUARE-TIE-RADAR2
If the intercepted signal is a Square Tie radar, the contact is
  using a missile fire-control radar in the direction of ownship.
Question?  WHAT IS THE INFERRED-TYPE OF CONTACT1
Type:                            Support           Plausibility

CARRIER:                         .02636711         .1246497
CRUISER:                         .02989827         .1281809
DESTROYER:                       .03943238         .137715
FRIGATE:                         .01616047         .1144431
AMPHIBIOUS:                      .01342259         .1117052
SUBMARINE:                       .02105637         .119339
SMALL-FIGHTING-SHIP:             .1043268          .2026094
FAST-ATTACK/PATROL-CRAFT:        .2982748          .3965574
PATROL-CRAFT:                    .0561144          .154397
INTELL-COLLECTOR:                .01567102         .1139536
SURVEY/RESEARCH:                 .005402734        .1036853
FLEET-AUXIL-MED/LRG:             .02774377         .1260264
FLEET-AUXIL-SMALL:               .0268845          .1251671
SMALL-BOAT:                      .02463102         .1229136
MERCHANT:                        .03126466         .05878379
FISHING:                         .07938433         .1776669
OTHER-COMMER/PRIVATE:            .06533772         .1636203
DEBRIS:                          .0203445          .1186271
```

```
The most likely type is FAST-ATTACK/PATROL-CRAFT.

I don't know.
Question?  Quit
Leaving EXPLAIN
 Thank you for your interest in the STAMMER system.
NIL
_(LOGOUT)
@POP

[PHOTO:  Recording terminated  Wed 8-Sep-82 1:11PM]
```